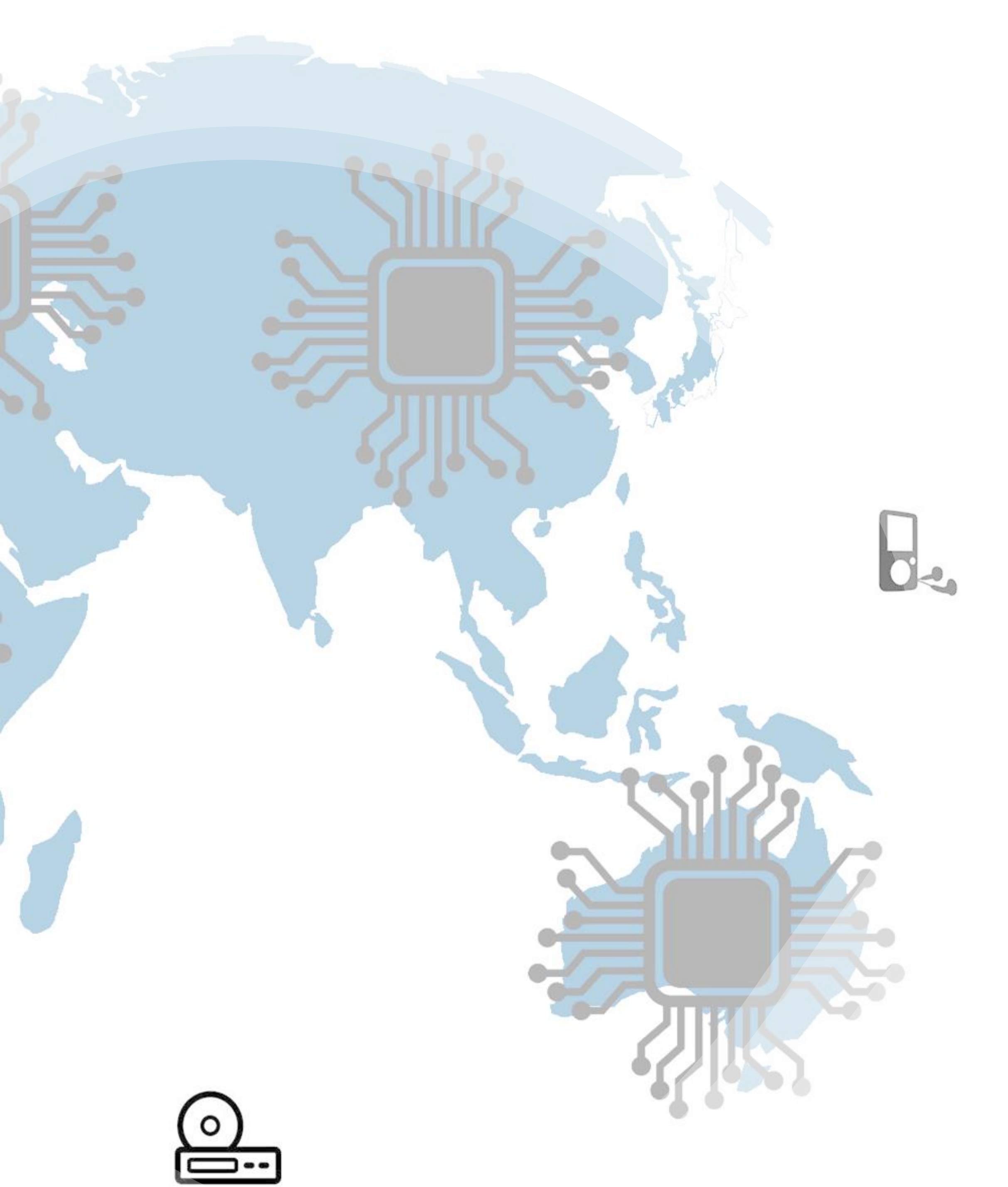

cRTOS: A Linux-compatible compounded RTOS based on NuttX, Linux and Jailhouse

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NuttX Online Workshop

About the Speaker

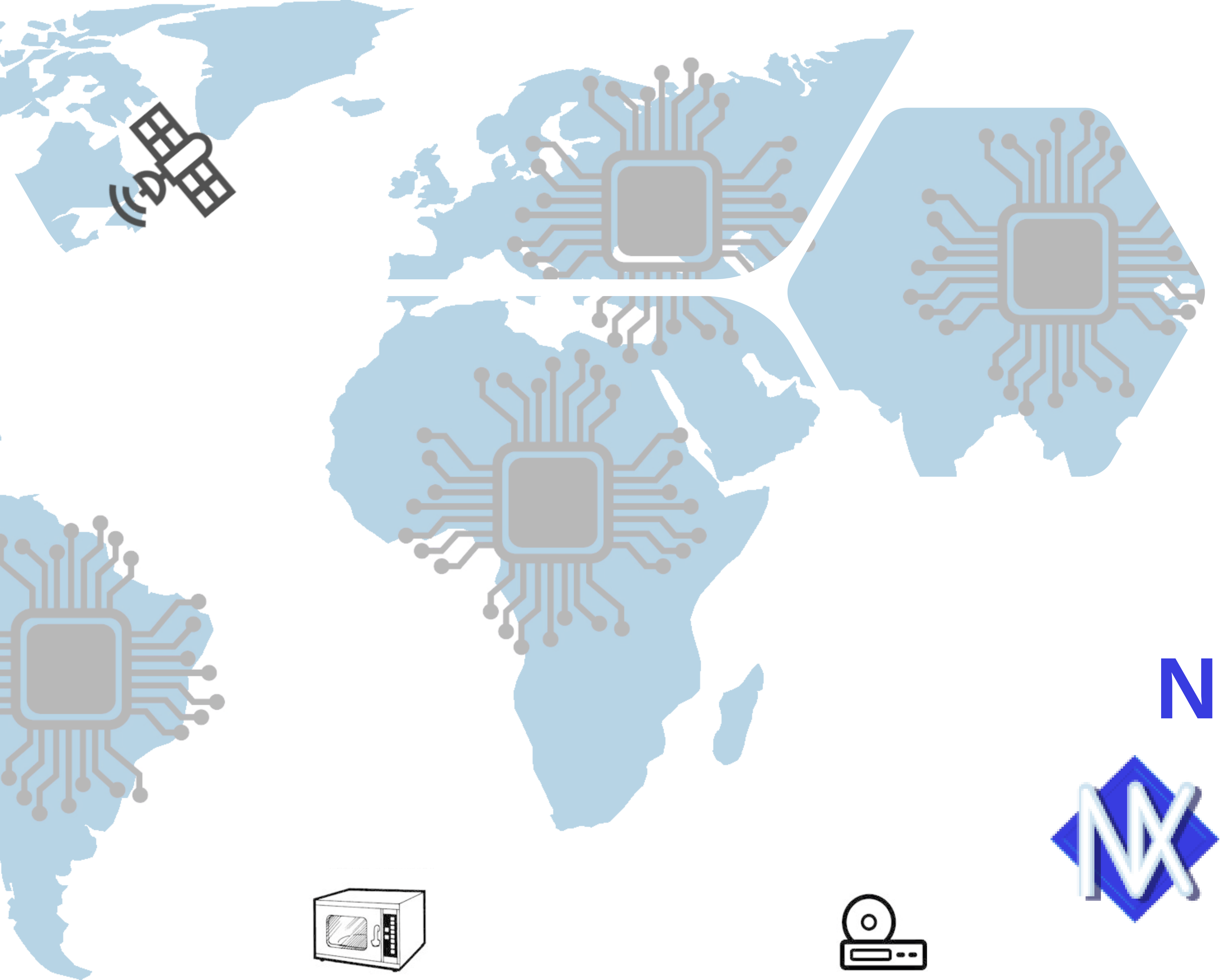
- Chung-Fan Yang
- Creator of the x86-64 port of NuttX
- From Taiwan, working in Japan
- Software Engineer at Fixstars Corporation
  - https://www.fixstars.com/en/
  - Software / Hardware
    based optimization, acceleration
- Hobby:
  - Embedded system
  - Poking around system software

Outline

- Introduction – What is cRTOS?
- Implementation
- Handling System calls
- Performance of cRTOS
- Demo
- Issues & Discussions

Academic publication

- Developed during my years in University of Tsukuba, Japan
- *“Obtaining hard real-time performance and rich Linux features in a compounded real-time operating system by a partitioning hypervisor. “*
  - Chung-Fan Yang and Yasushi Shinjo. 2020.
  - In Proceedings of the 16th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments
  - DOI: https://doi.org/10.1145/3381052.3381323



Introduction

What’s cRTOS?

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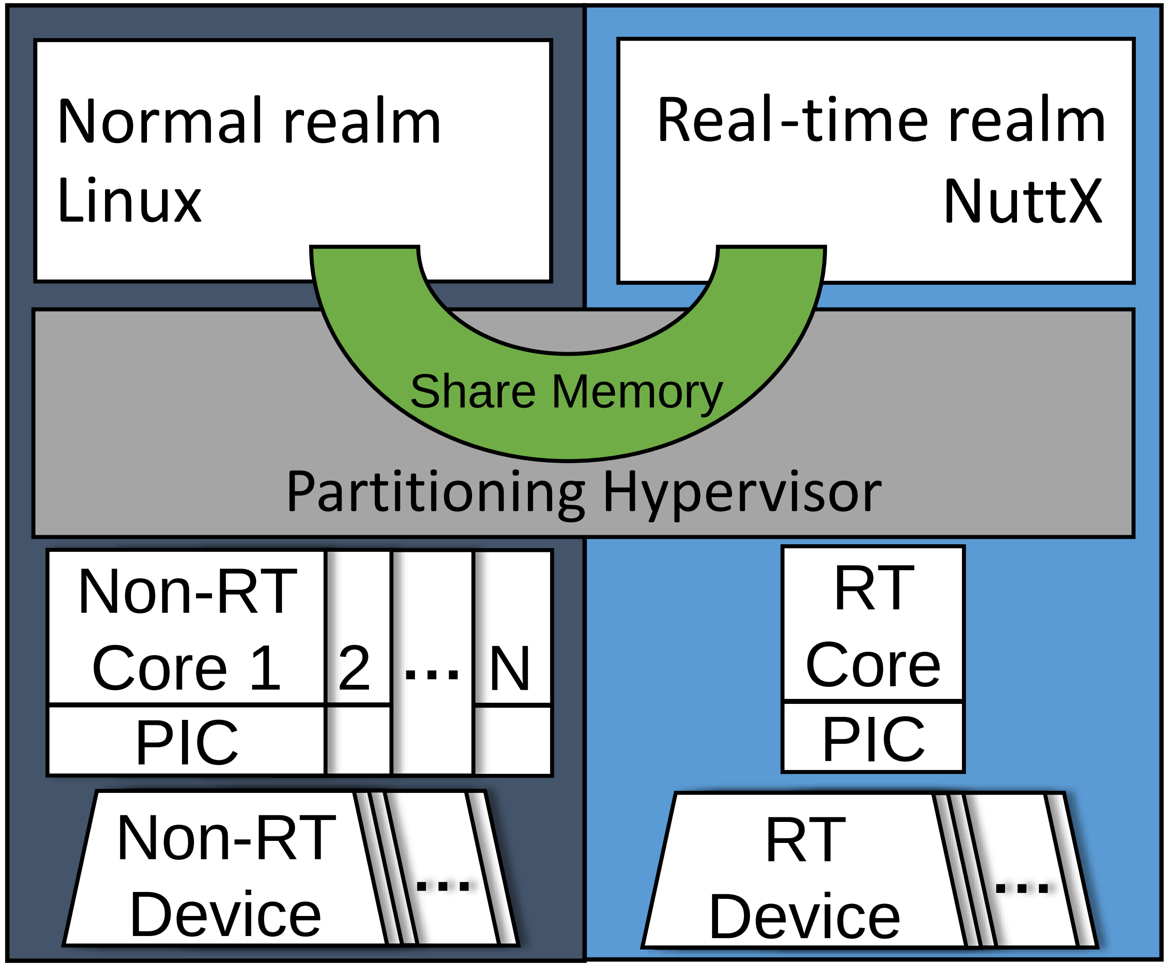
What is cRTOS(compounded RTOS)

1. Run a General-Purpose OS (GPOS) and a Real-Time OS (RTOS) together with a hypervisor
2. Snap them together as one big OS.
3. Run processes on this big OS.
   - Have access to both the benefits of the 2 OSs
   - Rich features of GPOS and Real-timeness of RTOS
4. User benefits from this easily programable real-time environment

System Overview

- Normal realm – Linux
  - Manages Non-RT devices
  - Soft real-time IRQ path
- Real-time realm – NuttX
  - Manages RT devices
  - Hard real-time IRQ path
  - Access Linux features with shared memory

Compounded RTOS



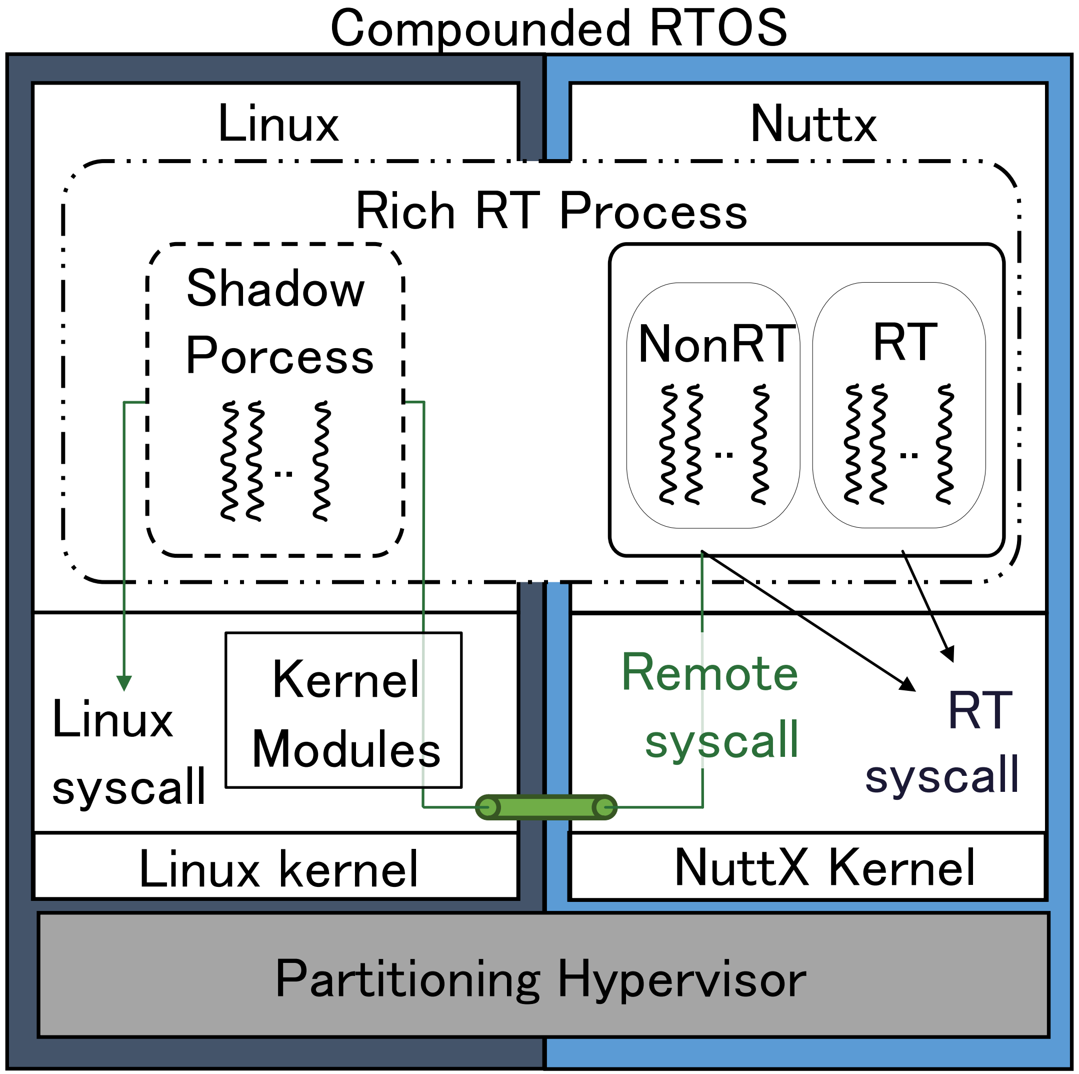
PIC: programmable interrupt controller

2 different viewpoints on benefits

- Benefits of cRTOS against other real-time extensions for Linux
  - Hard real-time is possible
  - No patching Linux kernel → very maintainable
  - Program real-time with Linux API ! → very easy to use
- Benefits of the Linux extension for NuttX (which is a part of cRTOS)
  - Let you execute (any) Linux programs in NuttX
  - No re-compiling, editing binary
  - Glibc and other libraries is usable
  - X window GUIs!

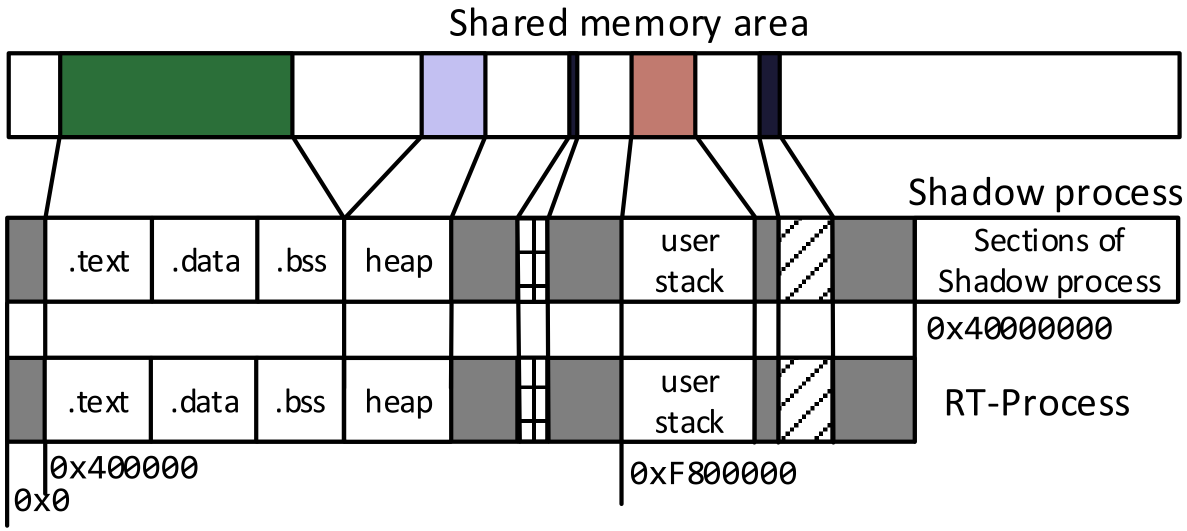
Concept of Rich real-time process

- Written with POSIX API and threads
- Executes in NuttX and Linux
- RT and non-RT threads
- RT threads:
  - Contain RT algorithms
  - Interact with NuttX and RT devices
  - E.g. Timer, CAN bus, SPI, I2C
- Non-RT threads:
  - Interact with Linux and Non-RT devices
  - Use rich features of GPOS
  - E.g. X window, TCP/IP



Shadow process

- Each rich RT process has a shadow process.
  - In the Linux as user process
    - 1:1 thread mapping.
    - Executes Linux system calls on behalf of Rich RT process.
  - Memory
    - Shared physical memory.
    - Same memory address space.
    - The same data at the same address in both process.



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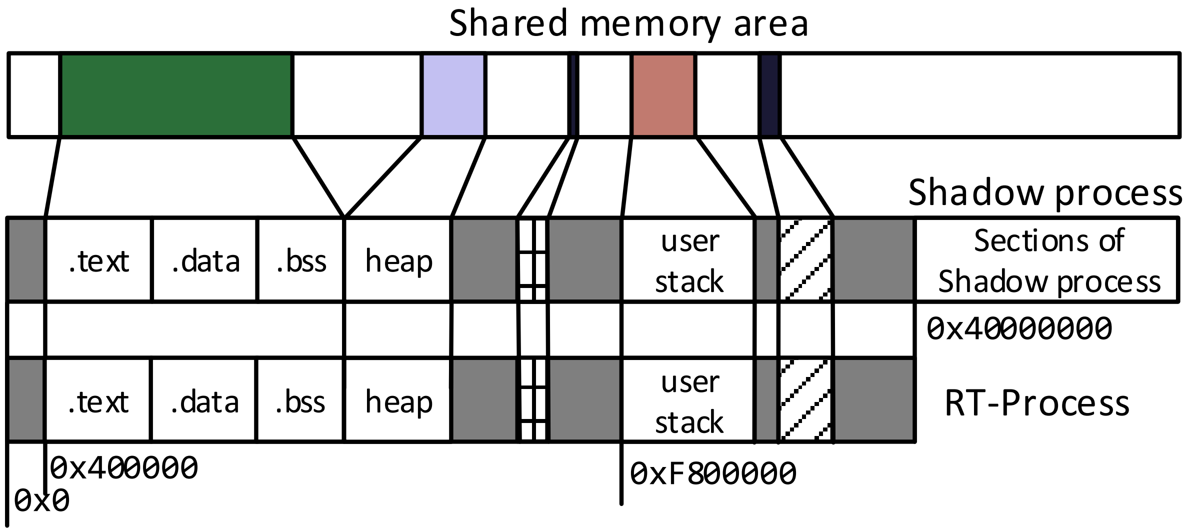
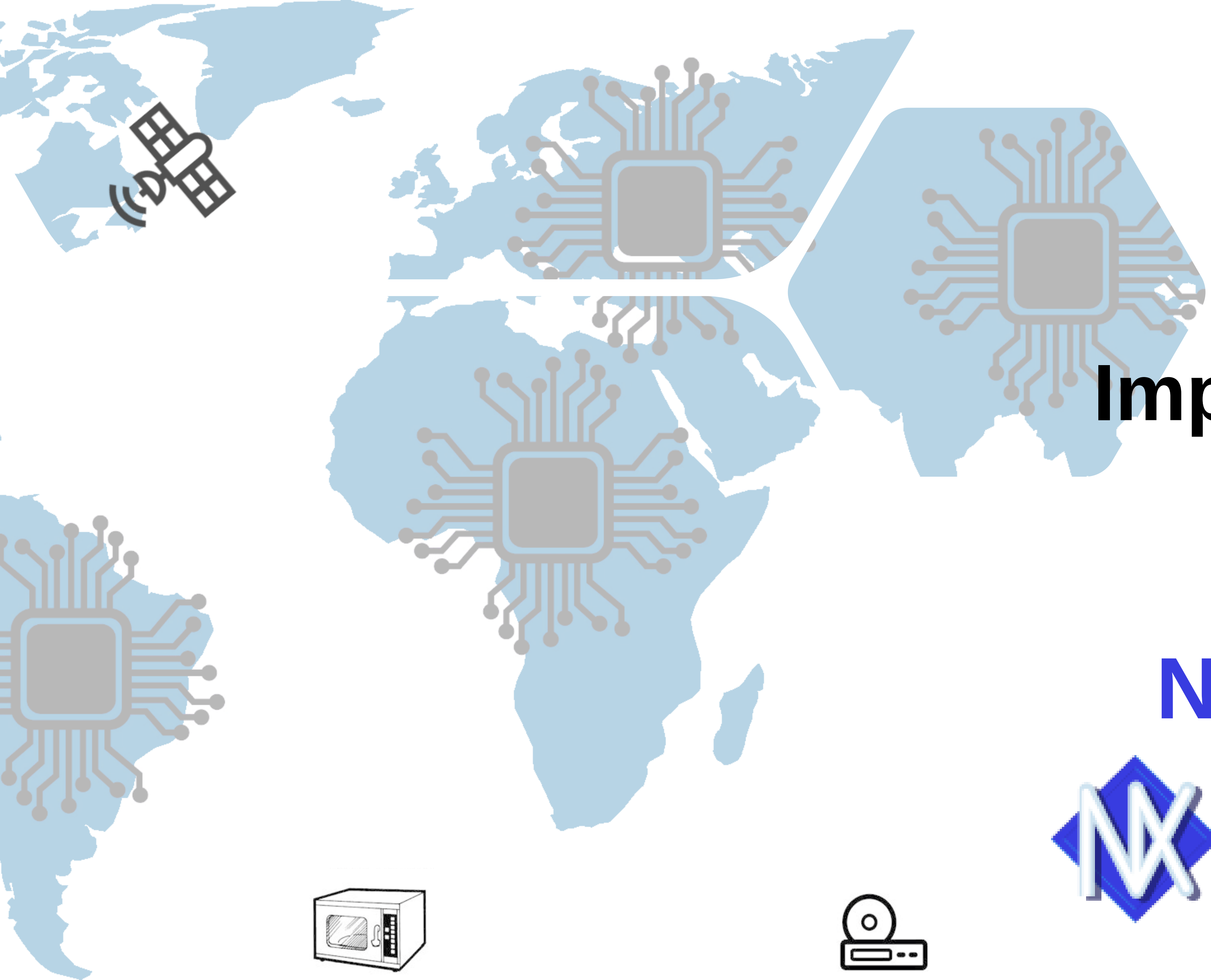


Very important attribute, will come back later



Implementation

POSIX is great

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Jailhouse - Creating 2 realms

- Current implementation used Jailhouse hypervisor[1]
  - Like Xen a Linux based Type-I hypervisor
    - Linux only as the bootloader and management interface
  - Partitioning hypervisor
  - Hardware resources are not shared.
    - No scheduling on vCPUs
    - Static memory allocation, might be shared
    - PCI-E device passthrough
  - Easily achieves hard real-time and feasible to runs RTOSs

[1] https://github.com/siemens/jailhouse

Linux – Normal realm with rich features

Well, it is the standard Linux everyone knows, nothing special.

No patching

Only 2 kernel modules for shared memory access

NuttX – Real-time realm

- Runs as another guest on Jailhouse
- Runs Linux program binaries
- Exploited the fact that
  - NuttX is POSIX confirming, so is Linux (mostly).
  - On source level, portable *nix program should work out of box.
  - System call set are very similar, main barrier is the ABI and VM (and the non-standard system calls which Linux had screwed up).

  - Provide a Linux compatibility layer, Whoosh, Linux program binaries should work.

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Development Goal

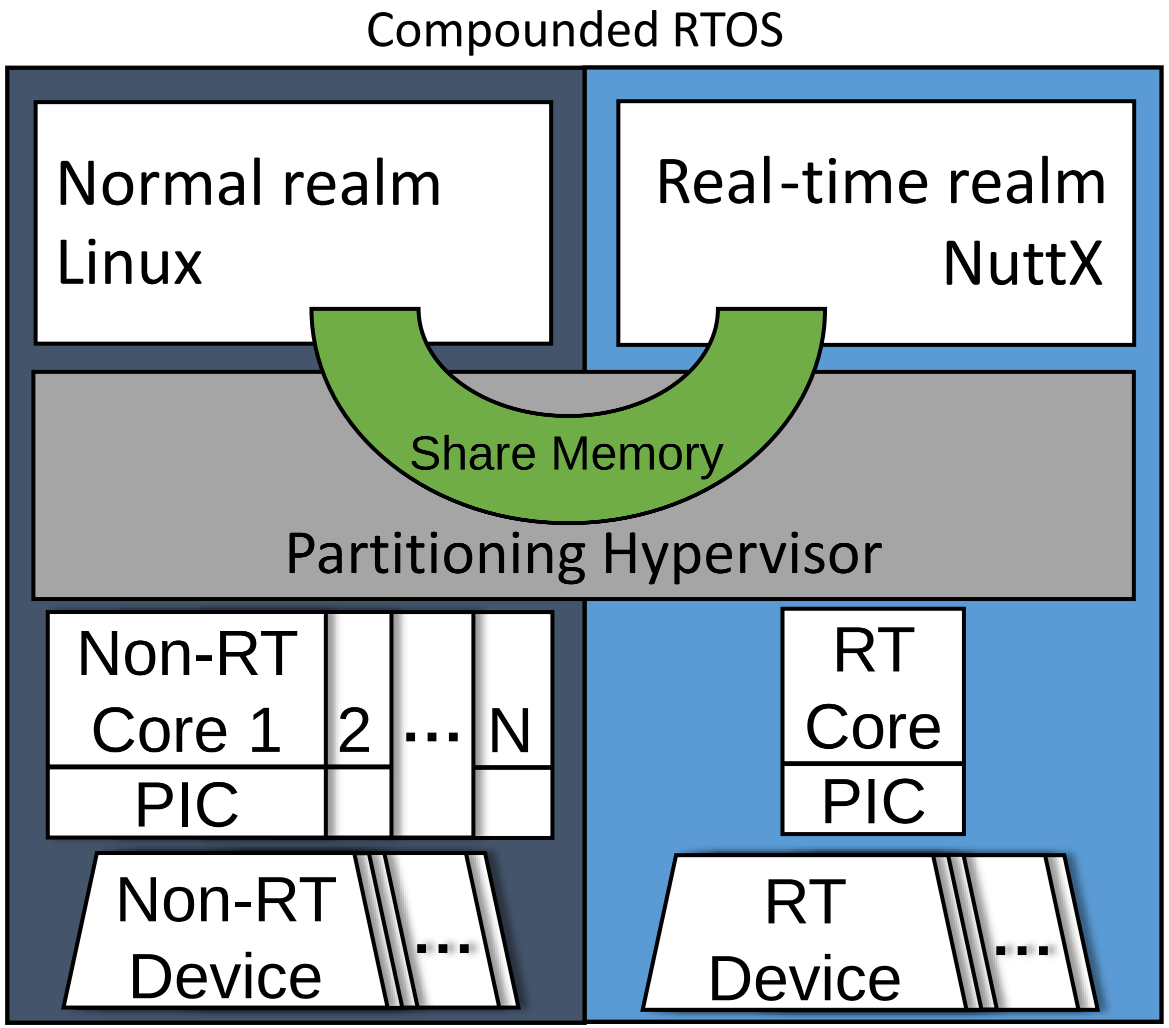
X86-64 NuttX

- By product of cRTOS, already merged to mainline
  - Try it and help report bugs!
- Jailhouse only support x86-64 and AArch64
  - And I happened to only have an x86-64 machine for development
- To make a Linux ABI compatible NuttX on x86-64
  - Ported NuttX to x86-64 with SystemV ABI
  - 50% done by compiler (Calling convention)
  - 50% hand coded (System call handler, XCP register set, FPU setting)

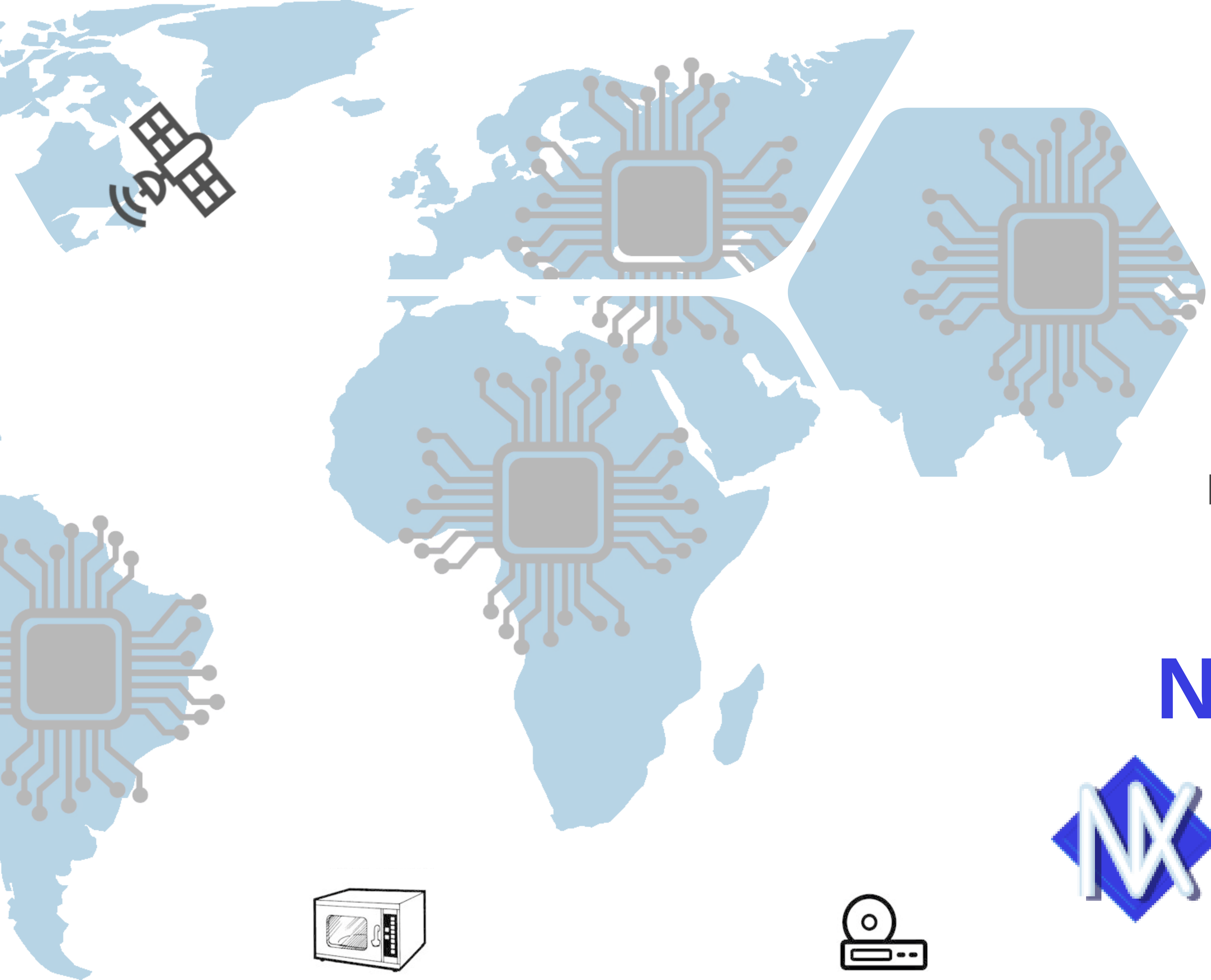
NuttX for Jailhouse

- Also a by product of cRTOS, already merged to mainline
  - Help testing!
- It can be used separately.
- Shared memory driver is implemented
  - Not yet merged.
  - PCI driver framework need to go first.
  - GPL license issue, need full rewrite.

System Overview



PIC: programmable interrupt controller



Handling System calls

Linux compatibility Layer

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Extending NuttX for Linux style process

- NuttX has some degree of protected or kernel build.
  - But quite far from a Linux compatible environment
- For simplicity,
  flat build is chosen and extended to support Linux style process.
  - Virtual memory supported is implemented.
  - Like Linux, kernel is in mapped to high memory
  - Process occupies lower memory
  - Dynamic memory mapping supported is added (mmap / munmap)
  - No actual protection between kernel and user space memory

Extending NuttX for Linux system calls

- Impractical to implement every Linux system call in NuttX
  - The existing system calls in NuttX cover a good variety of real-time usage
- We need a way to get over those
  - Nasty Linux specified system calls
  - System calls inessential to real-time
- We try to delegate those not important system calls to side-by-side Linux
  - Gives an excellent coverage
  - Trade-off between hard and soft real-time

System call handler

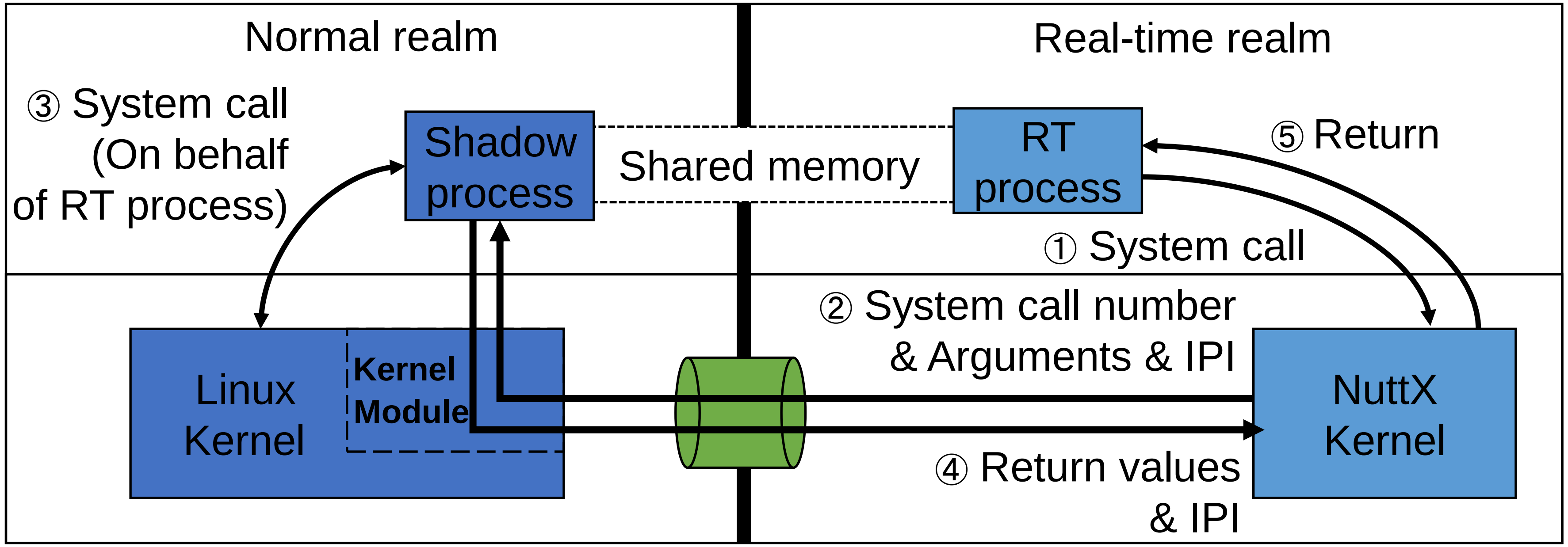
- Reuse the system call reservation mechanism
  - Lower 512 system calls are reserved for Linux system calls
  - Effectively moved NuttX system calls to 512~
- For 512~ calls, continues to function as-is
  - Native NuttX apps continues to function properly
- For 0~512 calls, either
  - In Nuttx → Real-time system call
  - Delegating to side-by -side Linux → Remote system call
- The selection of delegating or not is seamless,
  user code uses standard system call exception interface.

Real-time system calls

- Real-time related system call will be handled locally in NuttX.
  - Deterministic execution
  - Higher timing stability
- Access to local facilities
  - Synchronization: `semaphore, shared memory, etc.`
  - `Etc.`
- Access to RT devices
  - `open, read, write, etc.`

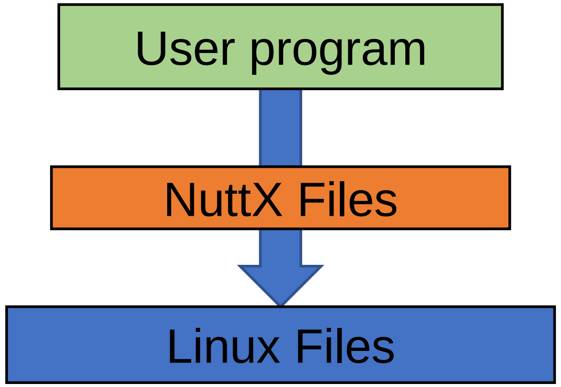
Remote system calls (RCSs)

- RSCs provide access to Linux features seamlessly
  - Access to non-RT devices, file systems, credentials
- Delegated system calls to Linux as messages via a queue.
  - Executed by corresponding shadow process
  - For handling pointers, shadow process shared same memory space



Overlay FS

- Open system call try NuttX files first before trying Linux files
- Effectively produce an Overlay FS



- The returning file descriptors is segregated, allow multiplexing
  - 0~4096: Linux files
  - 4096~ : NuttX files

Extending NuttX system calls

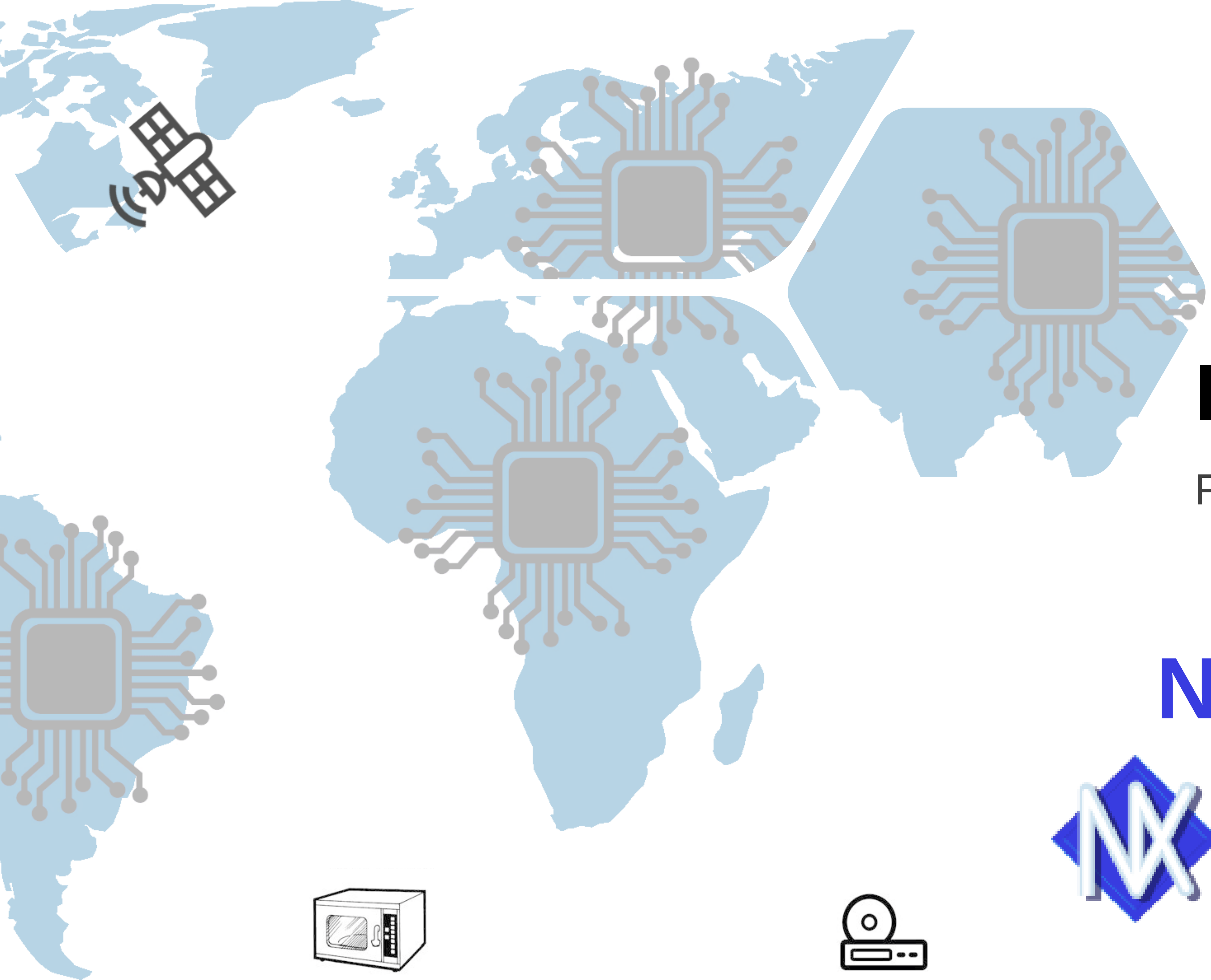
- Nonetheless, some of the system calls
  - Doesn’t exist in NuttX
  - Cannot be simply delegated to Linux because of semantics problem
- For example:
  - Process / threading related: `clone, fork, arch_prctl, etc.`
  - Memory management: `mmap, munmap, etc.`
  - SystemV IPC: `shmem, etc.`
  - Timer: `alarm, timer_create, etc.`
- Implemented those system calls
  (A lot less comparing to all of Linux system calls)
  - Most of them are stubs and wrappers

Dual system calls

- Among the extended system calls, some are dual system calls
  - Executed in both NuttX and Linux
- Synchronize the attributes between rich real-time and shadow process.
  - Memory map
  - 1:1 thread relationship
- `Clone, fork, exit, mmap, munmap, exec` are implemented as dual system calls

Starting a rich real-time process

- A daemon executes on Nuttx
- A loader program
  - On Linux side
  - Makes a remote exec call to the daemon on NuttX side
- The daemon creates a seed rich real-time process
  - The rich process calls exec system call to start the user appointed program.



Performance

First direct comparison of NuttX and Linux ever?

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Environment

Hardware

CPU	Intel Xeon 2650 v4 @ 2.2Ghz 10C/10T
RAM	32GB DDR4

Software

Jailhouse version	v0.9.1
Linux kernel version	v4.9.84
Nuttx version	v7.2

Configurations

Vanilla Linux	PREEMPT_RT
Proposed cRTOS / w vanilla Linux	Proposed cRTOS / w PREEMPT_RT Linux
Xenomai 3.0	

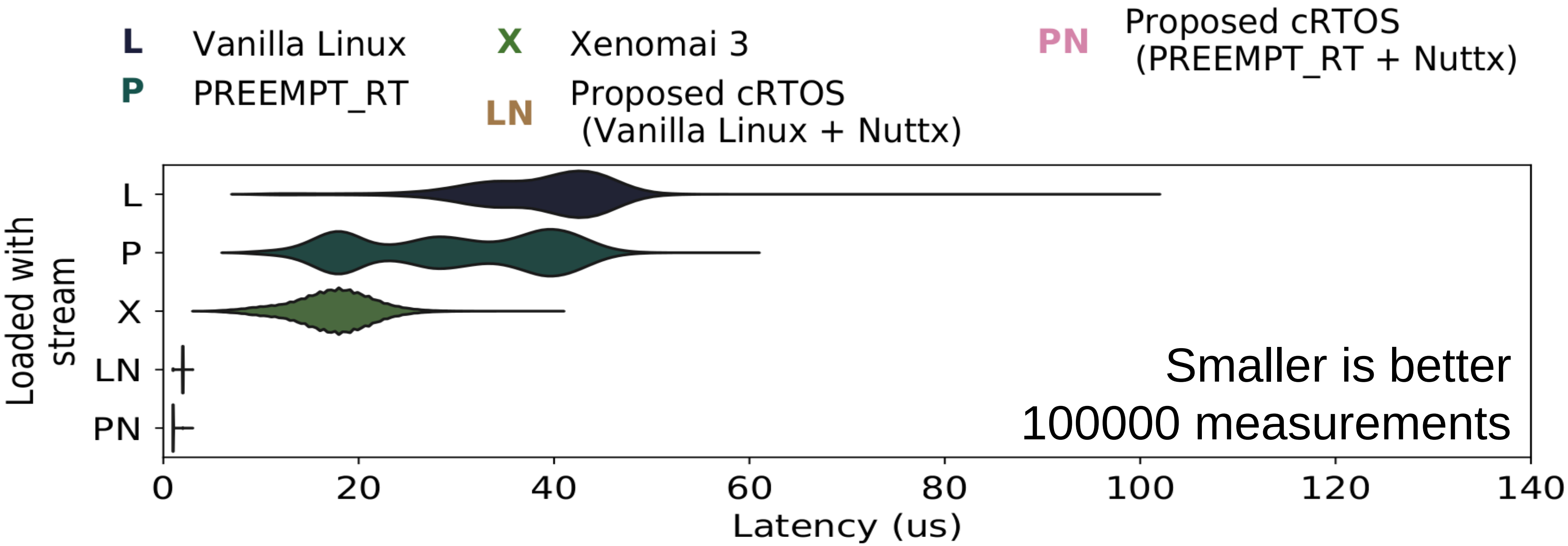
Cyclictest

- Cyclictest:
  - A thread set a timer and the timer expires.
  - Measures the elapsed time for accuracy.
- All configurations used the same binary,
  - Xenomai required a modified version of cyclictest.
- Parameter for cyclictest:
  - SCHED_FIFO, priority 90, interval 1ms, loop 100k times

- STREAM benchmark suite was used as extra load for hardware.

Cyclictest

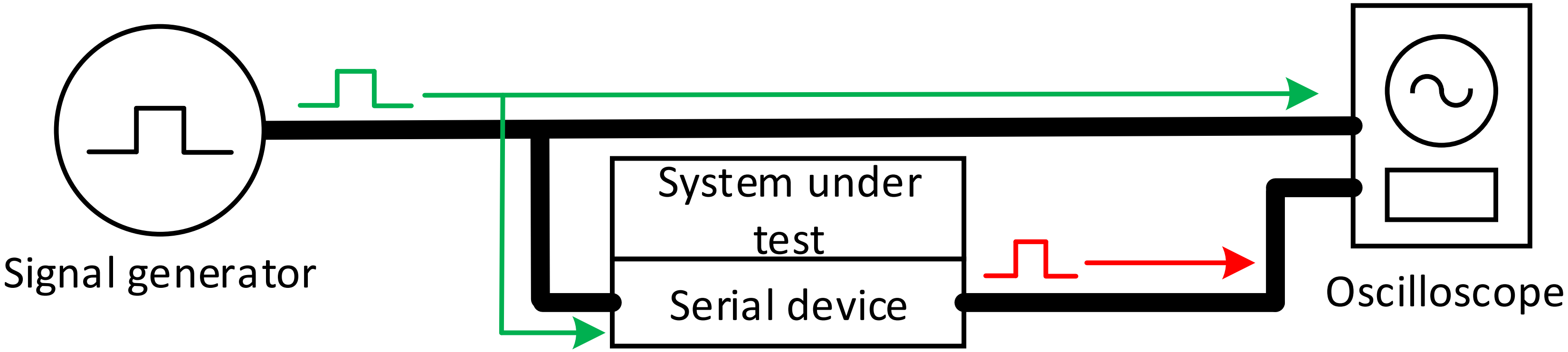
- The performance of real-time realm(NuttX) was the best
  - Latency: 4 us max / 4 us jitter
- Performance became better with PREEMPT_RT



Smaller is better
100000 measurements

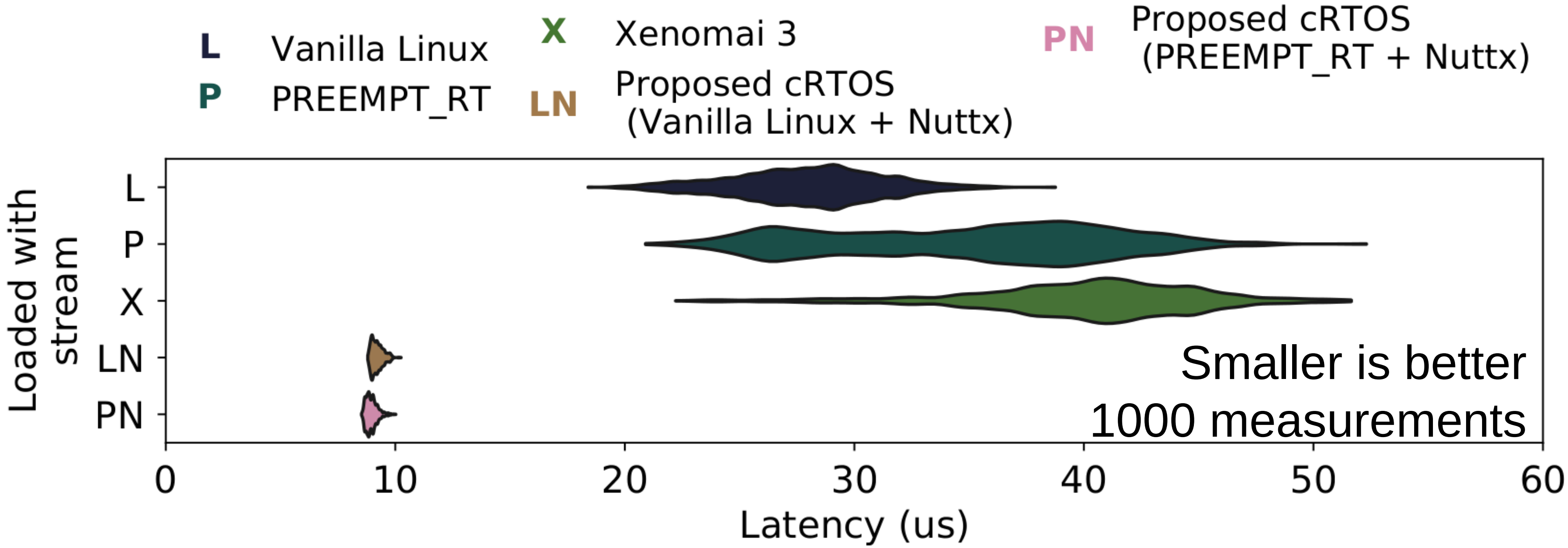
I/O Interrupt latency

- We measured the latency of a hardware interrupt.
- A serial device was attached to each configuration.
- The system was programed to generate an output upon an input is received.
- The gap between 2 pulses were measured with an oscilloscope.



I/O Interrupt latency

- The performance of cRTOS beats all other solution
  - Latency: 10 us max / 2 us jitter
- cRTOS's performance became better with PREEMPT_RT



Smaller is better
1000 measurements

System call latency

- Tested with original syscall micro-benchmark from Lmbench.
- Real-time system calls are faster than native Linux system calls.
  - vs PREEMPT_RT: over 4 times faster
- Remote system calls are quite slow

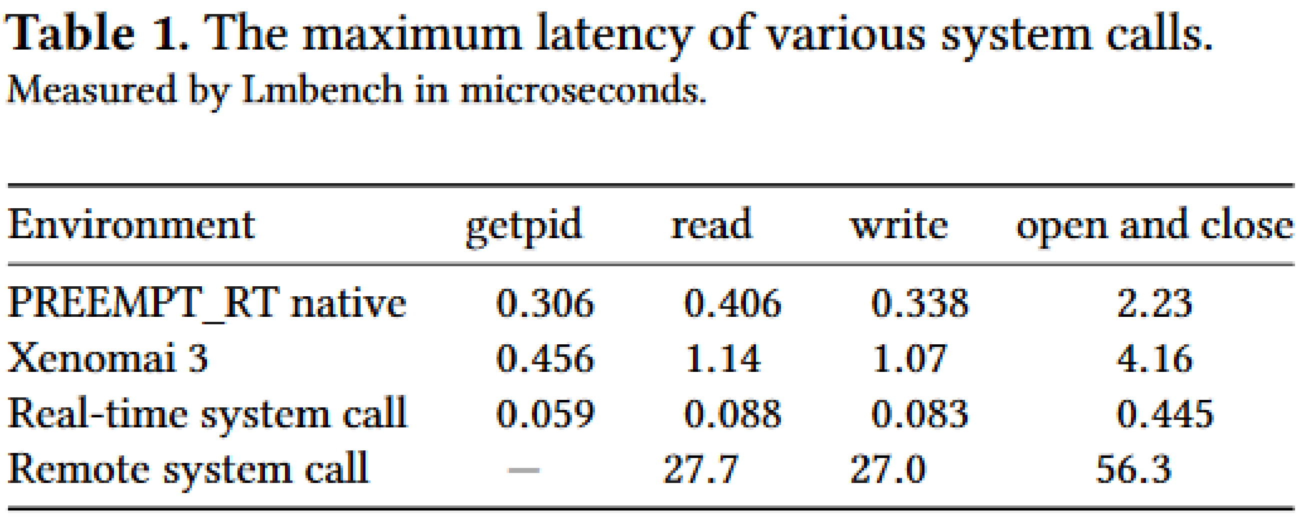


Table 1. The maximum latency of various system calls.
Measured by Lmbench in microseconds.

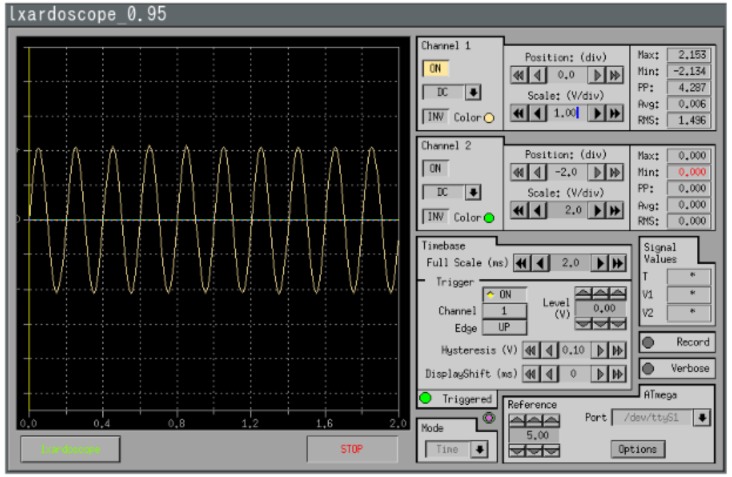
Environment	getpid	read	write	open and close
PREEMPT_RT native	0.306	0.406	0.338	2.23
Xenomai 3	0.456	1.14	1.07	4.16
Real-time system call	0.059	0.088	0.083	0.445
Remote system call	—	27.7	27.0	56.3

X window Applications in Nuttx!

vim

Ristretto

Ghost script



Channel 1: Position: (div) 0.0; Scale: (V/div) 1.00
Max: 2.153
Min: -2.134
PP: 4.287
Avg: 0.006
RMS: 1.496

Channel 2: Position: (div) -2.0; Scale: (V/div) 2.0
Max: 0.000
Min: 0.000
PP: 0.000
Avg: 0.000
RMS: 0.000

Full Scale (ms) 2.0
Trigger: ON
Channel 1
Edge UP
Level (V) 0.00
Hysteresis (V) 0.10
DisplayShift (ms) 0
T *
V1 *
V2 *
Reference 5.00
Port /dev/ttyS1

Xterm /w dash

Image magick

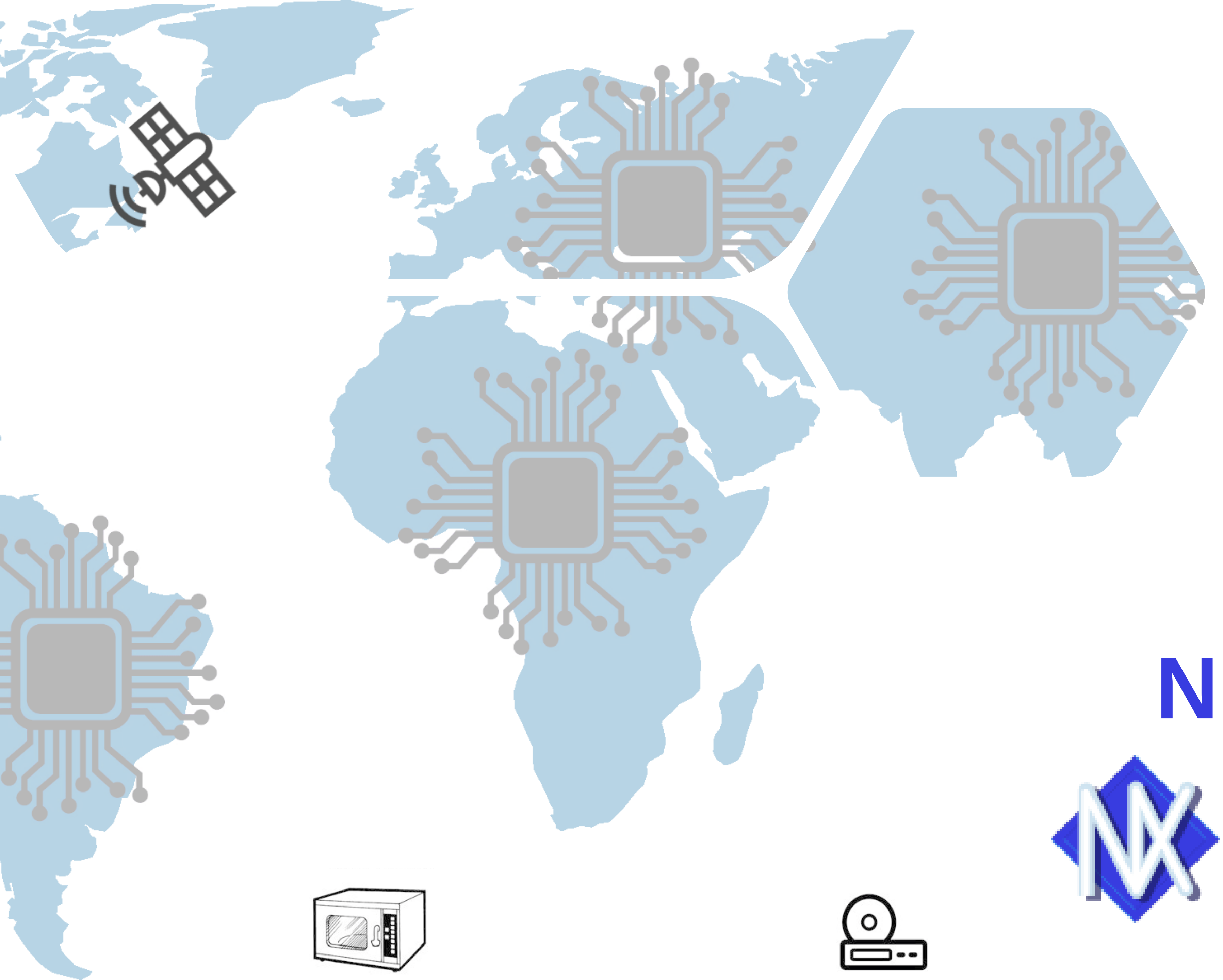
lxardoscope

Emacs

Gnome terminal

Gedit

Firefox



Demo

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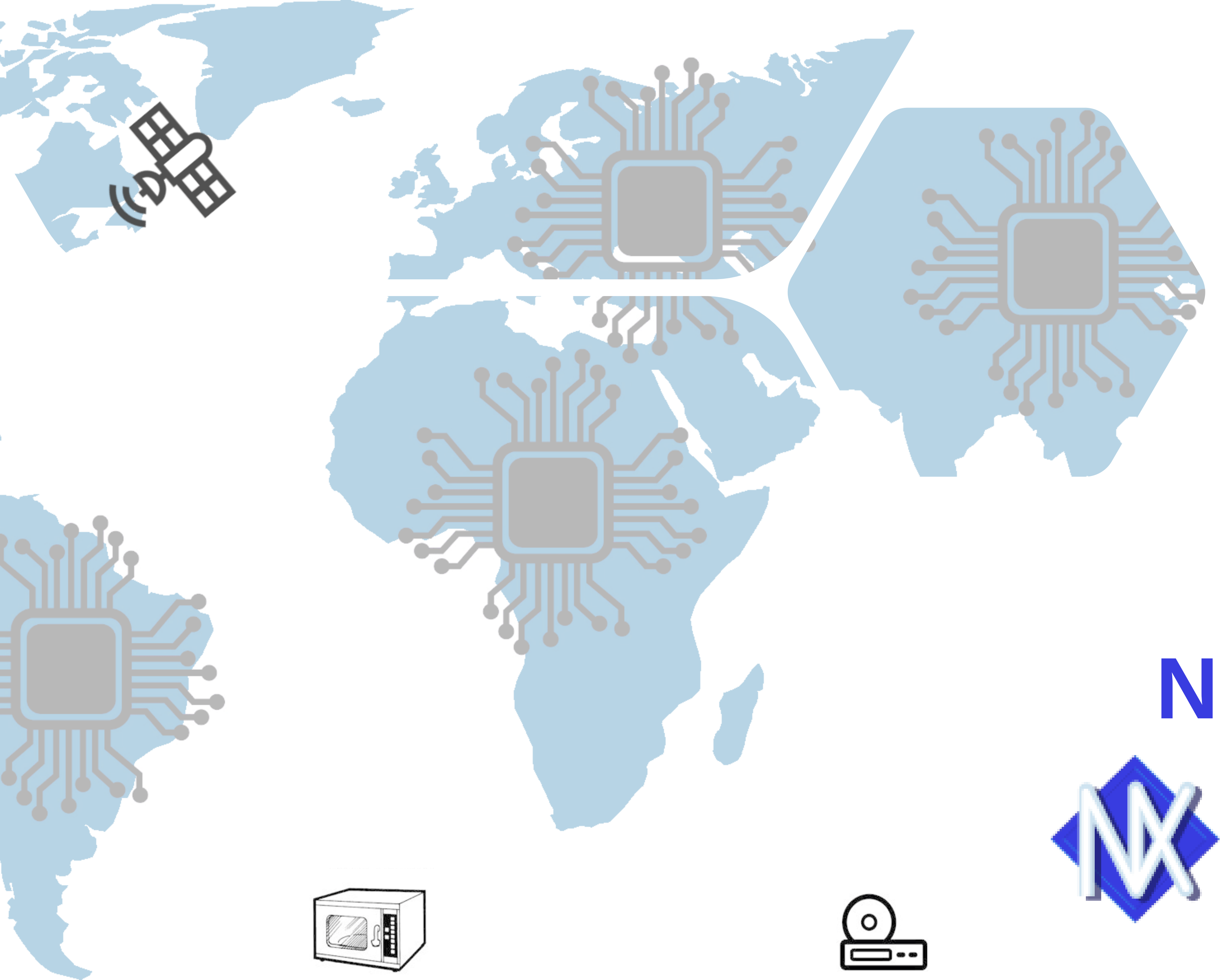

Issues & Discussions

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License Issues

- GPL2 and BSD licensed code exist in current source tree.
- Jailhouse’s share memory driver
  - Ported from Linux (which is GPL2, of course)
  - Rewrite is required, but how much is enough?
- Linux system call interface headers, a.k.a. UAPI headers
  - Contains system call related C struct, enum, MARCO definitions.
  - Required to parse and translate flags and structure into NuttX form.
  - GPL2 with “user program” exemptions, but we are not a “user program” in Linux!
  - Will a rewrite will save us?

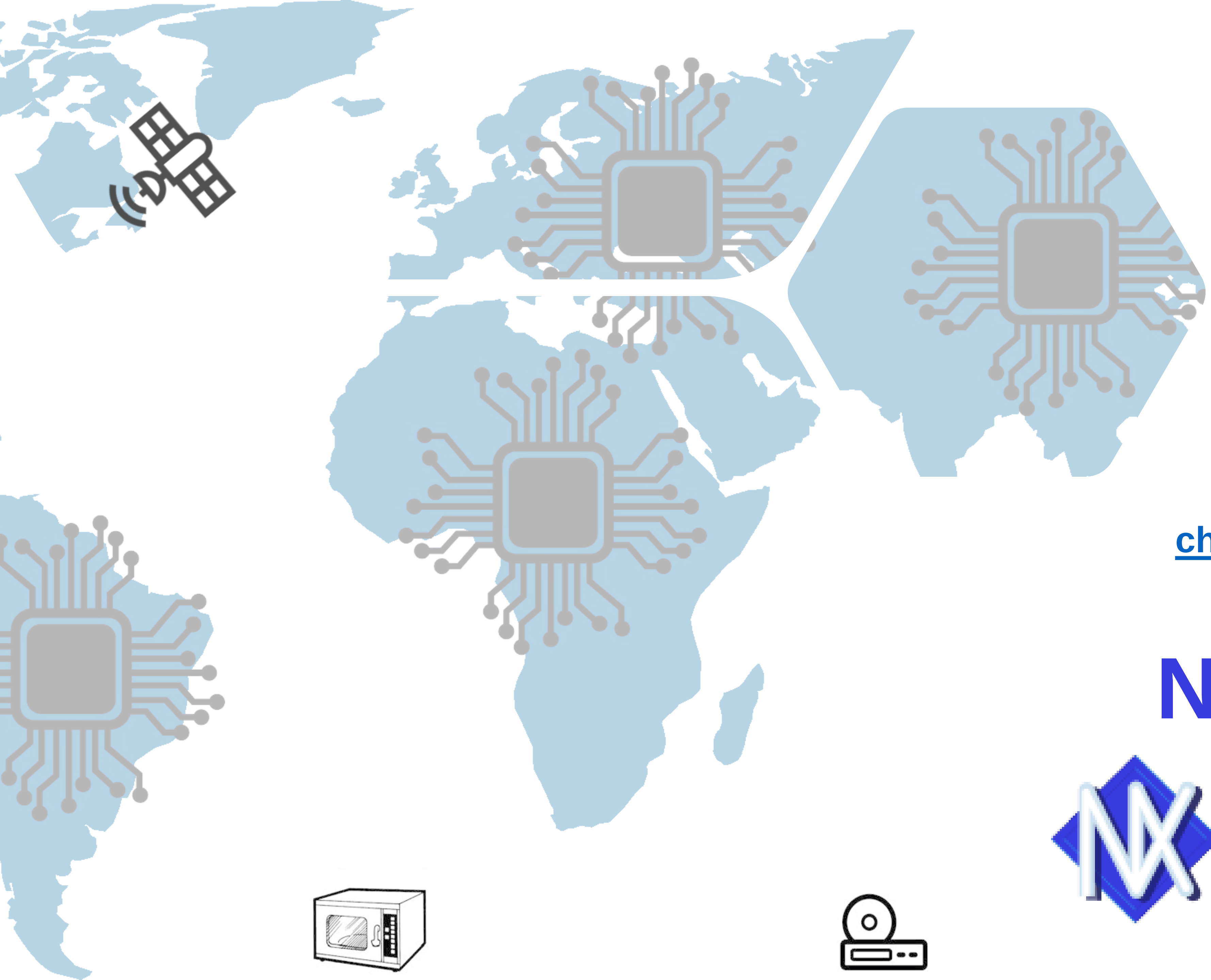
Future work

- Contributions are welcome
  - Require more people to test this on more boards and applications
  - Porting to AArch64?
    (Jailhouse and Linux is available, so it is very possible)
- Current maintained out of mainline
- Might make its way into the mainline
  - Prove such model is practical in use and beneficial for NuttX community
  - If the license issues are settled

Source Code:

- Hosted on the Github page of Fixstars
  - https://github.com/fixstars/cRTOS

- Ported to Linux 5.4, Nuttx 9.1, Jailhouse 0.12
  - Open tickets if you find any issues!



THE APACHE SOFTWARE FOUNDATION

Thank you!

Questions?

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Or the nuttx.event forum

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Thank you!